CHAPTER 2
LITERATURE

2.1 INTRODUCTION

This chapter provides the review of the past research efforts related to vibration signature analysis of the rolling element bearing to identify the incipient faults, properties of lubricant, synthesis of nano particle and tribological characterization of the nano lubricants. Bearings are the critical mechanical elements supporting the rotating machines and early detection of fault in bearing avoids the catastrophic failure of the machinery (Tandon, 1994). The detection of failure of bearing by different methods have been explored by researchers for the past three decades. Literature survey reveals that most of the engineering applications require proper diagnostic technique to identify the bearing failure well in advance. Prediction of failure requires a wide range of experimental data related to vibration for developing prompt lubrication system.

2.2 VIBRATION ANALYSIS OF BEARINGS – EXPERIMENTAL STUDY

A vibration-based signal analysis have been performed in the time domain (Amarnath & Shrinidhi 2004 and Choudhury & Tandon 1998) and the frequency domain (Randall et al 2001 and Stack et al 2006), or combination of time and frequency domain (Du & Yang 2006 and Luo et al 2003). Statistical indexes such as the root mean square (RMS) value, the crest factor, or the kurtosis have been used to detect the bearing fault in the time-domain
analysis. When a monitoring index exceeds certain threshold value, it is believed that a bearing is damaged. And also determining the appropriate thresholds has been difficult since it may vary in different applications.

Frequency domain methods have been the most commonly and widely used approach in bearing fault detection, by which the bearing defects have been detected, based on the analysis of spectral information. The frequency-domain analysis have an edge over advantage than time domain analysis, due to the ease of identification and isolation of certain frequency components of interest (Tandon & Choudhury 1999). The health conditions of a bearings have been assessed by examining the fault-related characteristic frequency components in the spectral analysis (Mcfaden & Smith 1984). To analyse the machinery defects the frequency-based techniques are not suitable because of non-stationary signals generated by the components of the machinery (Jardine et al 2006).

Amarnath & Shrinidhi (2004) reported that, defected elements in roller bearing generate vibration frequencies at a rotational frequency of each bearing component. Tandon (1994) used the equations (2.1) – (2.3) to identify the fault characteristic frequencies. Besides, a remarkable work was carried out with vibration analysis on roller bearing with inner race, outer race and roller defect by theoretical and practical manner. The malfunctioning frequencies were listed and the results were presented in Table 2.1. All the above frequencies appear in the frequency domain analysis report as a peak or with the side bands were denoted by Igarashi & Hamada (1982), Tandon (1994) and Nakra (1993).

Osuagwu & Thomas (1982) found that, identifying these fault frequencies (significant peak) are difficult because of masking of the vibrational signal due to external noise unless the defect is sufficiently large in size.
Inner race malfunction frequency \( (f_i) \)

\[
f_i = \frac{n}{2} f_r \left[ 1 + \left( \frac{BD}{PD} \right) \cos \beta \right] \tag{2.1}
\]

Outer race malfunction frequency \( (f_o) \)

\[
f_o = \frac{n}{2} f_r \left[ 1 - \left( \frac{BD}{PD} \right) \cos \beta \right] \tag{2.2}
\]

Roller Malfunction frequency \( (f_r) \), due to local fault on rolling element

\[
f_r = \left( \frac{PD}{BD} \right) f_r \left[ 1 - \left( \frac{BD}{PD} \right)^2 \cos \beta \right] \tag{2.3}
\]

Table 2.1 Comparison of fault frequency data by analytical and experimental

<table>
<thead>
<tr>
<th>Inner race defect</th>
<th>Outer race defect</th>
<th>Roller malfunction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental (Hz)</td>
<td>Analytical (Hz)</td>
<td>Experimental (Hz)</td>
</tr>
<tr>
<td>137</td>
<td>137.85</td>
<td>95</td>
</tr>
<tr>
<td>275</td>
<td></td>
<td>190</td>
</tr>
<tr>
<td>413</td>
<td></td>
<td>286</td>
</tr>
<tr>
<td>551</td>
<td></td>
<td>477</td>
</tr>
<tr>
<td>827</td>
<td></td>
<td>668</td>
</tr>
</tbody>
</table>

Lacey et al (2008) included the geometrical imperfections like eccentricity, waviness, and diameter variation along with the defects. The altered fault frequency values were presented along with the different method of prediction of defects. Muthukumarasamy & Ganeriwala (2010), presented the importance of selection of spectrum resolution to identify the faults with a
case study. Experiments were conducted using a defective bearing under different spectral lines as shown in Table 2.2. Finally it is proven that, a very high resolution is needed to resolve the fault frequencies as distinct peaks when they are close to the multiples of shaft speed or any other frequency component.

Table 2.2 Selection of spectral resolution to identify the fault frequency

<table>
<thead>
<tr>
<th>Spectral Lines</th>
<th>Resolution (Hz)</th>
<th>Resolution (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>400.00</td>
<td>24000</td>
</tr>
<tr>
<td>200</td>
<td>200.00</td>
<td>12000</td>
</tr>
<tr>
<td>400</td>
<td>100.00</td>
<td>6000</td>
</tr>
<tr>
<td>800</td>
<td>50.00</td>
<td>3000</td>
</tr>
<tr>
<td>1600</td>
<td>25.00</td>
<td>1500</td>
</tr>
<tr>
<td>3200</td>
<td>12.50</td>
<td>750</td>
</tr>
<tr>
<td>6400</td>
<td>6.25</td>
<td>375</td>
</tr>
<tr>
<td>12800</td>
<td>3.125</td>
<td>187.5</td>
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<tr>
<td>25600</td>
<td>1.5625</td>
<td>93.75</td>
</tr>
<tr>
<td>51200</td>
<td>0.7813</td>
<td>46.875</td>
</tr>
<tr>
<td>102400</td>
<td>0.3906</td>
<td>23.438</td>
</tr>
</tbody>
</table>

Ganeshkumar & Krishnaswamy (2009) developed a low cost bearing tester to identify an incipient fault in the bearing by using an accelerometer and virtual instrumentation software. The standard bearing was fitted on one end of the shaft and the test bearing on the other end. The vibration tones of the test bearing was compared with the standard bearing and fault decision was made by the control logic. Similarly an advance diagnostic system for remote condition monitoring of induction motor bearing was proposed by Gupta (2008) using wavelet analysis with the help of VI
software. The feature also allows to remotely monitor a number of machines in an industry simultaneously through internet/online. Ahmed A Elfeky et al (2007) investigated the effect of single point defect and generalized roughness on ball bearing by machine vibration and stator current analysis. The raise and repetition of harmonics of frequencies and presence of side bands in both faults were evident to identify corresponding fault.

Bob Jones (1998) demonstrated the usefulness of time domain analysis of vibration data, to detect the deterioration of the extremely low speed (0.5 rpm) ball bearing in steel mill kettle applications. Mohamadi Monavar et al (2008) investigated the roller bearing defect running under 700,1500 and 2100 rpm by time and frequency domain analysis, data captured by X-Viber device.

Many researchers (McFadden & Smith 1984, Alfredson & Mathew 1985, Harris 1991, Su & Lin 1992, Tandon 1994, Martin & Honarvar 1995, Tse et al 2001, McInerny & Dai 2003, Zeki Kiral & Karagulle 2003 and Patil 2008, Khonsari & Booser 2008) have used the statistical method for identifying the defects in the ball bearing by time domain analysis of vibration signature using peak-to-peak amplitude, root mean square, crest factor and kurtosis. Spectrum analysis (frequency domain) was used to identify the exact location of defect and reported a difficulty in finding the correlation between defect size and vibration magnitude since, it varies from system to system.

Ebrahim Ebrahim (2012) reported that, the detection of inner race and roller defect was more difficult to identify while using FFT with envelope detection. But the other way, using time-frequency response generated by WA detects the inner race and ball defects in the high frequency region.


Combination of artificial neural networks (ANN) with discrete or continuous wavelet techniques (CWT) applied by Al-Raheem et al (2008), Rafiee et al (2007), Samantha & Al-Balushi (2003) and Subrahmanyam & Sujatha (1997) helped to identify the defects early, compared to the statistical methods. Matej Tadina & Miha Boltezar (2011) developed an improved model of the bearing in order to investigate the vibrations of a ball bearing during run-up. The developed model was used to simulate the defected bearing and to identify the defects by envelop method. The CWT was able to detect the simulated local bearing’s fault during run-up.

2.3 VIBRATION ANALYSIS OF BEARINGS UNDER LUBRICATION

Vibration behavior of roller bearings with respect to lubricant viscosity was analysed by Serrato et al (2007). The vibration level is determined through bearing vibration data from each of the lubrication condition under various bearing speeds. The results showed that changing oil viscosity in roller bearings only affected the bearing’s vibration in high frequency band (600-10,000 Hz). Halme (2002) focused on wear debris analysis and vibration measurement of an oil circulating lubricated ball bearing. Compared to the light intensity test results, vibrations analysis resulted in providing poor sensitivity to identify the healthy and fault bearing over the test duration of 37 hours in the test rig. After 31 hours of test, a change in vibration acceleration rms was observed. The reason may be that, at end of the test the large size particles quadrupled and application of heavy load on bearing caused the increase of vibration. The optimum combination and application of techniques like particle counting, vibration measurement
and light transmission test, led to monitor the condition of the oil lubricated bearing and update prognosis for the bearing’s life time.

Maru (2007) focused on studying the effect of solid contamination in lubricant through vibration and wear measurement by adding quartz particle in different size and concentration. The vibration levels increasing during the test duration was related to an effect produced by the wear of the bearing elements. The direct relationship between the contaminant particle concentration and was vibration apparently seen. The particle size did not have effect on the vibration due to intensified particle settling as the test progress. Also the result showed that rms values of the vibration did not change due to the radial load, but depended on the wear of the bearing elements.

The extension of the previous work was carried out by Maru et al (2007) by comparing the vibration between ball and roller bearing with the same quartz particle in different proportions. The results of clear oil vibration test showed that roller bearings vibrated 1.25 times more than the ball bearing vibrations, due to the smaller values of minimum oil film thickness (λ). Reduction of λ increased the metal asperity contact contributed for higher wear. Besides, the number of contacts, variation in the internal clearance also contributed for the distinct behaviour. On the contaminated oil, the vibration of ball bearing seemed to be higher than the roller bearing. The different weightage of contamination and wear contributed for vibration as a function of concentration.

Juha Miettinen (2000) used an acoustic emission (AE) method to monitor the lubrication condition of grease lubricated ball bearings (SKF 6206). The AE tests with clear and contaminated grease (quartz, high speed steel powder, iron powder and combination steel and iron oxide) were conducted. The minimum concentration of contaminants were raised the AE
pluses compared to clear grease vibration. The hardness of the contaminants were reflected in AE pulse count measurement than AE time signal. The vibration levels were higher for clean and re-greased contaminated bearing, compared to clear grease operated bearing.

Peng et al (2005) experimented the effectiveness of vibration analysis and wear debris analysis under controlled experimental conditions in predicting the machine faults. Both tests correlated well in identifying the catastrophic failure of the gear box elements well in advance by their results. The fault frequencies generated in the gear box supported bearing were in direct relationship with the five set of lubricating conditions (normal, insufficient lubricant, silica contaminated lubricant, iron powder contaminated lubricant and combination second and fourth condition) experimented.

Farcas & Gaffitanu (1999) focused on analyzing the effect of grease lubrication with the contaminants in roller or ball bearing at the temperature of 60 – 70°C and at higher operating speeds. Two type of greases (A and B) were selected for, determining lubricant service life at different operating temperature, monitoring lubricant fibroid structure, finding drop contact angle and experimental validation of minimum fil thickness by experimentation. The following equation was derived to find the optimum operating speed of the ball bearing,

\[ n_{opt} = 24.12 \left[ \frac{\gamma_l (1 + \cos \alpha)}{\rho D h^{1.5} d^{0.5}} \right]^{-0.5} \]  

(2.4)

The A and B lubricated bearings were set to run in the test rig and the observed results correlated well with the equation (2.4). High film thickness observed in the test starting and reduced as the time progressed, due to the deterioration of the fibroid structure of grease.
Cann (1996) clarified the mechanisms of film formation by greases in rolling Elasto Hydro Dynamic (EHD) contacts by experimentation. The author has also discussed the lubricating mechanism and nature of film formation as shown in Figure 2.1 with the help of a model bearing. The result showed that the scale effects were important and this process occurs closer to the contact in grease lubricated systems. The hydrodynamic film at the side supports the solid film developed at the centre to carry the loads. The research provided a basic understanding of film formation and this shall be extended for more complex problems.

![Figure 2.1 Grease lubrication in a model bearing contact](image)

Juha Miettinen (2000) investigated the performance of grease lubricated bearings in realistic conditions. Thickener concentration, viscosity, bleeding rate and consistency were studied and results were compared with the oil lubrication. The acoustic emission method was employed to study the fundamental behavior of grease lubrication. Measurement of film thickness was done in ball and disc type equipment. The result showed that AE pulse method was the best condition monitoring technique for studying the time dependent behavior of grease lubricated ball bearings in situ.
Wang et al (2000) reviewed the research carried out in ceramic rolling bearings and compared it with the conventional steel bearing. The result showed that ceramic bearings can be used at severe lubrications and wear conditions such as extreme pressure, temperature and high speed applications. Under high speed and heavy load application, due to oil churning the ceramic bearing was found to be underperforming compared to the steel bearing. The corrosive resistant nature of the silicon nitride ceramic bearings made it suitable to work with the lubricants.

### 2.4 SYNTHESIS OF NANO COPPER OXIDE PARTICLE

A proper conglomerate of theoretical and experimental efforts were needed to select the nano lubrication system for a specific application. Synthesis of CuO nano particle were done by many researchers using different methods like sonochemical method (Vijaya Kumar et al 2000), electrolytic cathode deposition method (Kavita Borgohain et al 2000 and Theivasanthi & Alagar 2011), sol–gel technique (Eliseev et al 2000), one-step solid state reaction method at room temperature (Xu et al 2000), thermal decomposition of precursors (Hui Wang et al 2002) and aquas method (Amrut S Lanje et al 2010) and so on.

Khanna et al (2008) synthesized oleic acid capped copper nano particle using sodium formaldehyde sulfoxylate (SFS) in aqueous medium. The prepared particles were characterized by XRD, SEM, EDAX. Loss of weight of particle due to the surfactant was found using thermo gravimetric analysis (TGA). And the presence of oleic acid coating over the nano-Cu particle was confirmed with the Fourier transform infra-red spectroscopy (FTIR) measurements.

The large scale production of nano-Cu particle was explored by researchers (Wu et al 2007 and Yueli Wen et al 2012). Szu-Han Wu et al (2004) produced nano-CuO particles by reducing the cupric chloride with hydrazine in the aqueous CTAB solution. The investigation of size control of copper nano particle was reported by Hassan Hashemipour et al (2011) using chemical and electro chemical process. By controlling the electrolyte concentration and current density, an average particle size of 10 nm was obtained in the process.

The other chemical method of preparing nano CuO particle was proposed by Ugwekar & Lakhawat (2012). The nano CuO crystalline particle of size 26-29 nm was synthesized using copper nitrate and sodium bicarbonate. The XRD and SEM results of calcination at 350°C and 450°C produced sphere shaped nano-CuO particles in agglomerated condition.

2.5 PERFORMANCE OF NANO PARTICLE AS AN ADDITIVE

The nanomaterials have significant role in the development of advance lubrication technology. A lot of research was conducted on the tribological performance of nano-particle as an additive with the lubricant. It also enriches the properties of extreme pressure, anti-wear, anti-friction, anti-scuffing, improved load carrying capacity and even more based on the nano-material. Min et al (2008) reviewed the characteristics of nano materials and
nano particles used as an additive with the lubricant. The effect of nano particle size, shape, nanostructure, surface functionalization and concentration provides a better understanding to select the proper nano particle for the application. Pullela K Sarma et al (2011) prepared the Nano Cu and TiO$_2$ particles suspended in Racer-2 commercial lubricant in different mass proportions. The test was made with a commercial two wheeler engine equipped with hydraulic loading facility. The collected data were related with the break thermal efficiency of the engine and the mathematical model developed correlated well with the experimental results with reasonable accuracy. The introduction of nano – CuO particle with the Racer 2 lubricant provided better performance than the lubricant with TiO$_2$ particle.

Kwangho Lee et al (2009) proved that the spherical shaped nano particle mixed lubricant (CB and graphite) showed a low frictional resistance than the fibrous structured nano particles (CNFs/CNTs) mixed lubricant on disc-on-disc tribometer test.

Liu et al (2004) investigated the deposition of copper layer due to the frictional heat developed during rotation (called mending effect) by conducting pin-on-disk experiments and verified using SEM and STM results. Yujin Hwang et al (2011) depicted the possible mechanism of lubrication in nano-lubricated system as depicted in the Figure 2.2.

![Possible lubrication mechanism by applying nano-lubricant](image)

**Figure 2.2 Possible lubrication mechanism by applying nano-lubricant**
The participation of lubricant in creating (a) direct effect and (b) secondary effect was defined clearly by disc-on-disc tribological test. The surface modification occurred by nano particle abrasion enhanced the lubrication property compared to the mineral lubricant.

Hsiau Yuh Chu et al (2010) investigated the anti-scuffing property of the nano-diamond particles suspended in the lubricating oil. The optimum of 3vol.% of diamond particle reduced the mean friction coefficient and mean wear loss coefficient compared to the base lubricant. The volume of 0.2% of copper oxide nano particles were added with the 50CC lubricant by He-long Yu et al (2008). The average wear scar diameter was reduced by 25% and the friction coefficient by 20% compared to 50CC base oil. The tribo-mechanical tests reported that the formation of low hardness, thin copper protection film over the contacting surface resulted in friction reduction. Pingping Ye et al (2002) explored the synthesis and tribological study of Nickel oxythiomolybdate (NiMO$_2$S$_2$) nanoparticles suspended in Pentaerythritol tetraester (PETE) lubricant. The good anti-friction, load carrying capacity and anti-wear properties were exhibited by the nano-lubricant compared with the conventional synthetic lubricant even at elevated temperatures.

Wu et al (2007) compared the tribological properties of two lubricating oils (API-SF engine oil and a Base oil) with CuO, TiO$_2$, and Nano-Diamond nanoparticles used as additives. In particular, the nano-CuO particles added APF-SF oil and base oil reduced the friction coefficient by 18% and 6% and the worn scar depth by 17% and 79% respectively, compared to the base oil without nano particles. Nano-copper oxide particle modified with Dialkyldithiophosphate (DDP) was investigated by Jingfang Zhou et al (2000) The DDP-Nano CuO suspended paraffin oil and the four
ball wear test proved that the superior anti-friction properties depend on the size of the nano particle.

Surface modified nano-CuO versus non-modified nano-CuO produces a significant anti-wear behaviour and its interaction effects were explored. Anti-wear behaviour of nano particles of CuO, ZnO and ZrO\textsubscript{2} suspended polyalphaolefin (PAO 6) tested under extreme pressure conditions (as per ASTM D2783 standards) were reported by Hernandez Battez et al (2008). The particles were separately dispersed at 0.5%, 1.0% and 2.0%wt. in PAO 6 using an ultrasonic probe for 2 min. The suspensions with 2% of nano CuO particle exhibited higher friction coefficient and lowest wear for the same nanoparticle content of other two materials. Increase of CuO, ZnO and ZrO\textsubscript{2} content in base oil increased their deposition on wear surfaces, yet the tribological behaviour of ZnO and ZrO\textsubscript{2} suspensions exacerbated in comparison with CuO.

The SEM and EDS results of the experiments were facilitated to find the anti-wear mechanism. The tribo-sintering of nano particles on the wear surfaces reduced the metal-to-metal contact and acted as load-bearing areas. The surface modification of nano particles by using Oleic acid treatment was experimented by Yang et al (2012) and Xiaohong Kang et al (2008).

Xiaohong Kang et al (2008) experiments helped to select a proper ratio of mixing of oleic acid with copper sulphide producing good anti-wear properties and low friction coefficient. The molar ratio of 1:1 provided better results than the other ratios. Juozas Padgurskas et al (2013) also investigated the anti-wear property of nano CuO particles with nano Fe and nano Co particles. The triboloical test results showed that, the nano CuO particle as a single or in combination with other nano particle was effective in reducing the wear compared to the base oil. The EDX analysis reports helped to identify
the presence of metal particle in the surface of the wear tested balls. Xing Peng De et al (2009) investigated the tribological behaviour of OA modified diamond nano particle in liquid paraffin showed better anti-wear and anti-friction than the pure paraffin oil. The structure of OA modified particles were observed by SEM and IR and dispersivity by nano particle analyzer. Similarly the SiO$_2$ particles in liquid paraffin was investigated by Xing Peng De et al (2010) using ball-on ring wear test. The results showed the optimal concentration of nano-SiO$_2$ particle in reducing friction and wear. Nabeel Rashin & Hemalatha (2013) experimented the viscosity properties of nano-CuO mixed coconut oil. The nano sized copper oxide particles were synthesized by two step (sol-gel) method and characterized using XRD and HRTEM. The effect of shear rate, concentration and temperature on viscosity were found by experimentation and compared with the theoretical models (Einstein, Batchelor and Wang models). The reason for the variation from the theoretical model being that, the conventional theories have not considered the particle size, shear rate, solution chemistry, measurement technique, particle aggregation and resultant shape effects. A new correlation was found to relate the viscosity with the concentration and temperature for the prepared nano-copper oxide mixed coconut oil.

The effect of aggregation of nano-copper oxide particle on viscosity was researched by Madhusree Kole & Dey (2011). An average aggregate sized about 7 times more than the average particle size continued to maintain the same size within 24 hours of preparation. The increased volume fraction of nano CuO particle with the gear oil exhibited the non-Newtonian behaviour of fluid. The increase in internal shear stress (due to increase of particles) contributed for the increase in viscosity. The viscosity was increased by three times than the base fluid due to the increase of volume fraction (0.005 to 0.025) of nano-CuO particle. But the trend of reduction in the viscosity was found with the increase of temperature similar to the other
nano fluids (Sahoo et al 2009, Namburu et al 2007a, Namburu et al 2007b and Kulkarni et al 2006). Li et al (2006) used dialkyldithiophosphate coated Cu, Ag, TiO$_2$ and LaF$_3$ nanoparticles in the concentration of 0.5% with Liquid paraffin. The experiments were carried out with four ball wear tests as per ASTM D2783 procedure. The results were compared with the commercially and most widely used AW/EP additive called zinc butyloctyldithiophosphate (ZDDP). Among the other particle nano-Cu particles, exhibited the lowest WSD and better AW property than ZDDP. Since the shear between contacting surface increased, this initiated the melting and welding of particle and thus produced an adherent layer over the harder material.

2.6 GAPS IDENTIFIED THROUGH EARLIER INVESTIGATIONS

Even though there are numerous reports in the literature about the measuring vibration of defected bearing, synthesis of nano copper oxide, tribological behaviour of nano particle suspended lubricant, no work has been done on the study of vibration damping ability of the lubricant. By going through the literature it was evident that some of the following points were not fully addressed by the researchers.

- The use of prediction tools such as vibration signature analysis have been reported in many literatures. But filtering the required data from the spectrum of signal has not been discussed much in the literature.

- Importance of MOFT and lubrication factor towards the creation of lubrication regimes on different lubricants have been reported rarely in the literatures.

- Though much work has been reported on anti-wear and anti-friction properties of nano additive lubricant, comparatively
less has been reported on the selection of suitable nano particle and its concentration for lubricant application.

- A possibility that the incorporation of nano-CuO particle could provide damping property to the lubricant has not been adequately addressed so far and there is inadequate data available about the phenomena behind the improved damping.

- Even though there are numerous reports in literature about the tribological behavior of nano lubricants, limited work has been done on the effect of viscosity on damping characteristics. Not enough data have been available on the effect of viscosity on vibration characteristics.

- Studies carried out worldwide on vibration of bearing have largely been experimental and the performance evaluation of developed nano-fluid for ball bearing application is rare.

It is understood from the literature survey that nanoparticle influences the enhancement of mechanical and tribological properties of the mixing media. The copper oxide nano particle was selected to blend with the lubricants having three different viscosities grade lubricant. The lubricant added with CuO nanoparticle improves the tribological properties, and in turn this improves the vibration suppression ability.